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Underwater Sonar for Simultaneous Localization and Mapping - Intelligent Robotics Research Center, Monash University

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The following highlighted reports summarize activities of S&T Associate Directors of the Office of Naval Research International Field Office (ONR IFO) in Europe and Asia. The complete newsletters and reports are available under the authors' by-line on the ONR IFO homepage: http://www.ehis.navy.mil/ http://www.ehis.navy.mil/onrnews.htm or ONR IFO-Asia homepage: http://www.onr.navy.mil/onrasia/, or by email to respective authors.

Keywords

Sonar processing, ultrasonic devices, broadband acoustics, object tracking, mapping, unmanned undersea vehicle, robotics

1. Summary

Recently, the Office of Naval Research (ONR) International Field Office (IFO) conducted a site visit to the Intelligent Robotics Research Center (IRRC) at Monash University, Melbourne Australia, to investigate the naval application (particularly for unmanned vehicles) of a new research project entitled "Underwater Sonar

for Simultaneous Localization and Mapping." The project will research new underwater sonar sensing approaches to enable multiple target tracking and feature extraction in both natural and man-made underwater environments. Data from the new sonar sensor will be combined with inertial and water speed sensors to produce accurate and consistent underwater maps. This research will assist autonomous navigation by underwater vehicles, and is consistent with ONR component technologies and system concepts to enable the application of small mobile robotic platform systems to mine countermeasures missions particularly in the very shallow water, surf zone and beach zone environments. This Newsletter is designed to inform national and international scientist, research and governmental institutions and international organizations about potential research collaboration.

2. Background *by CDR Butler, Dr. Jones, ONRIFO and Dr. Kleeman, IRRC*

Monash University, with seven campuses and 45,000 students in the Melbourne area, is Australia's largest university. Monash is involved in research in fields as diverse as education, injury prevention, information technology, medical science and engineering. The Intelligent Robotics Research Center (IRRC) resides within the Computer Systems Engineering group of the Department of Electrical and Computer Systems Engineering of Monash University. The major strengths of the IRRC at an internationally recognized level, are in the following areas: a) Machine Perception including image processing, ultrasonic sensing, tactile sensing, pattern recognition, computer vision, optical flow, range finding, olfactory sensing and interactive computer graphics; b) Robot Navigation, including localization, environmental modeling, simultaneous localization and map building (SLAM), and collision-free path planning.

ONRIFO met with Dr. Lindsay Kleeman, Associate Professor at IRRC. His research interests are Computer engineering, Very large-scale Integration (VLSI) design and Computer Aided Design (CAD), Digital design and performance, Robot localization, and Computer vision. Currently Dr. Kleeman’s work is focused on the vehicle sensors and in particular, the sonar sensors for object tracking. The sonar sensor array has applications in mobile robotics for localization and mapping of indoor environments. The ultrasonic sensor localizes and classifies multiple targets in two dimensions to ranges of up to 8 m. Targets separated by 10 mm can be discriminated.

Work commenced in 1993 on developing sensor deployments for air based ultrasonic sensing and in 1998 on real time implementations. Real time implementations have been made in two major areas: (a) PCI bus sonar system (b) DSP based sonar system.

(a) PCI bus sonar system

A four channel receiver, 4 channel transmitter 1 MHz sample rate sonar acquisition system has been developed and interfaced to a PCI bus for real time data throughput to a Pentium PC for processing. This device has been deployed as two independently panning sonar systems on a mobile robot. By using programmable transmit pulse hardware, a new double pulse coding technique has been implemented for transmitter coding so that the two systems can run together so that pulses from one sonar sensor can be rejected if received on the other system.

(b) DSP Based Sonar System

An Analog Devices 2181 DSP has been integrated into a new sonar system for two transmitters and two receivers. All data processing is performed onboard the system to minimize processing time and communication delays. The system hardware and software was completed in 1999. Real time target classification will be performed with this system even when the sensor is in motion. Classification will be achieved by simultaneous transmissions from two transmitters and an intelligent receiver system to unravel the echo pulses from both transmitters. The commercial potential for this system is being investigated.

The key element of Dr. Kleeman's work is the use of a two-element array (2 transmitter/receiver pairs) with a broadband short duration pulse. Digital Signal Processing is used to analyze the data. The increased frequency content of the pulses allows more precise object discrimination while the short duration limits the processing load. The sensors are mounted on a horizontally rotating mast, and attempt to track objects within their field of view. Common indoor landmarks such as planes corners and edges are located and classified with a multiple transducer sensor array. With the advanced sensor, the environment is scanned and the obtained features are classified into planes, corners, edges and unknowns. The feature map is only updated with the first three types of features. Being sharper and more realistic than other representations such as uncertainty/bayesian maps, continual localization is made possible. Accurate odometry information is derived from a pair of narrow unloaded encoder wheels. Discrete sonar observations are incrementally merged into partial planes to produce a realistic representation of the environment. Collinearity constraints among features are exploited to enhance state estimation. Although not yet implemented in real time, this work has provided a solution to provide concurrent mapping and localization whereby the vehicle is able to create a map of its environment without additional navigation information.

Dr. Lindsay Kleeman manages several robotics projects that include autonomous laboratory scale wheeled vehicles (roughly 50 kg). These vehicles are electrically propelled and have on-board computer guidance equipment with several sensors for navigation and object detection. Other related projects include larger robotic vehicles (over 1000 kg) that are intended for use in rough terrain. Visit http://www.ecse.monash.edu.au/centres/IRRC/index.html#Photos hyperlink for photos and movie demonstrations. Furthermore, Dr. Kleeman has links with J. Leonard of the Massachusetts Institute of Technology. Dr. Leonard is well known in the Unmanned Underwater Vehicle (UUV) field for his work on UUV navigation. Dr. Kleeman proposes to continue his investigative work with short-duration broadband sensors in the underwater environment.

3. Future Research (2000-2002) – Underwater Sonar for Simultaneous Localization and Mapping *by CDR Butler, ONRIFO and Dr. Kleeman, IRRC*

3.1 Aims, and Expected Outcomes

In summary, the research aims to use broad band underwater transducers to develop high speed, accurate target bearing, range and classification performance. Broad band pulses will be employed to speed up processing and give fine range discrimination.

Specific aims are to:

a. Research new underwater sonar sensing approaches to enable multiple target tracking and feature extraction in both natural and manmade underwater environments.

b. Investigate simultaneous localization and mapping filters for combining inertial, deadreckoning and the new sonar features onboard an underwater vehicle.
c. Demonstrate results using autonomous navigation experiments.

Dr. Kleeman has had considerable success in air sonar sensor design for range and bearing accuracy and target classification. See Associate Professor Lindsay Kleeman's online publications for more details. The underlying principles that have brought about this success are:

a. The generation and exploitation of physically based models of transmitters, wave propagation, reflection/diffraction and reception of ultrasound.
b. Application of optimal signal processing algorithms to the complete base band sonar received signal. This processing has resulted in significant improvements in sensor range and bearing accuracy.
c. Sensor configurations that result in dramatic performance improvement.

Using these principles Dr. Kleeman will attempt to produce a new effective fast and accurate target-classifying sonar sensor design. In the area of simultaneous localization and map building, the decomposition of global maps into linked local maps to reduce computation complexity in the maintenance and construction of the maps will be exercised in the area of underwater environments where the potential complexity is even higher. Thus new approaches to the generation of large-scale accurate underwater sonar maps will be a worthwhile outcome of this research.

3.2 The Challenges

Dr. Kleeman has identified many interesting challenges to be faced with the underwater environment compared to indoor "air" mobile robot environments:

a. No accurate odometry or deadreckoning sensors – the effects of ocean currents and the lack of any firm physical contact with the ocean floor or fixed structures removes the analogy of wheel encoder odometry available indoors. Underwater deadrecking systems rely on inertial sensors and water speed sensors – both of which suffer from greater drift problems than ground based robots. Moreover there is no guarantee that a sensor is ever stationary with respect to the environment.
b. Three dimensionality of the problem – this factor adds combinatorial complexity. The use of pressure based depth sensors provides good position sensing in one dimension.
c. Unstructured environmental features – the absence of geometric models (for example a plane is a useful target feature for indoor maps) makes map building more difficult. Natural terrain features need to be extracted that are easily identified from many positions so that position fixes can be obtained. This area is one of active research where little significant progress can be claimed.
d. Target clutter – often there is an over-abundance of sonar returns from fish, sea floor features close together which makes unique identification of targets challenging.
e. Ultrasonic propagation losses are much lower in water allowing the benefit of greater range of operation compared to air sensing where the maximum range achievable is less than 15 meters typically.

These items present several challenges for his research, and potential for other experts to contribute in collaborative development.

3.3 Research Approach

The initial stage of research will concentrate on the sonar sensor design. A single transmitter / three receiver prototype system, will be constructed from a mixture of commercially available transducers, power amplifiers and data acquisition systems. The use of at least three receivers will enable accurate bearing estimates to be produced of targets in three dimensions. The advantage of increased bearing accuracy is that target association problems are reduced when map building is undertaken later. The other obvious benefit is the increased localization accuracy and therefore improved map accuracy. Three-dimensional capability is required underwater due to three dimensional vehicle motion and the nature of the terrain.

The initial objective of this research is to evaluate physical models for the transmitter, propagation, echo production and reception of the ultrasonic signal in water at different frequencies for different target types and transmitter excitation patterns. Careful evaluation of specularity properties is required to investigate the development of appropriate sensor models and configurations. "Various literature suggest target specularity is observable at low frequencies (below 50 kHz where wavelengths are above 30 mm) and then for manmade structures such as pipes, smooth ship hulls and wharf structures" (quoting comments from Dr. Kleeman).

In uncluttered environments where pulse overlap is infrequent, the arrival time of an echo can be estimated using template matching (this technique is more commonly called replica correlation) - this technique relies on finding the maximum cross correlation between the echo and *a priori* stored pulse shapes. Template matching has been implemented in real time using dedicated DSP hardware for air based sonar. The approach is a promising candidate underwater and can be used with multiple receivers to produce extremely accurate bearing estimates. Should clutter be significant, narrow beam electrically steerable transmitter arrays can be used to reduce clutter and improve bearing angle estimates, at the expense of speed (since the transmit beam needs to be repeatedly fired to cover the area of interest). Steerable receiver arrays can also be employed with a significant increase in hardware required due to the increased data acquisition and processing load. However, repeated transmission can be avoided if received echoes are stored for later steering of the array. Vast computing resources are required to run this method in real time. This project will consider the different options in light of DSP power at the time of implementation.

Experimental work on the sensor modeling and data acquisition can be conducted with the assistance of the following generally available facilities in the Intelligent Robotics Research Center at Monash University:

a. A 9 meter diameter 2 meter deep tank
b. A Titan SII submersible remotely operated vehicle
c. Ocean going Wildcat Aluminum 24' Boat and tow vehicle.

From the established experimentally verified models more refined sensor hardware can be designed based on fast ADC devices and DSP processors. The integration of signal processing, data acquisition and hardware interfacing has been successfully performed for an air based sonar system using ADSP2181 devices as part of an Australian Research Council Large Grant entitled called Real Time Ultrasonic Processing. Satisfying the requirements for underwater operation adds an extra level of complexity and expense. However, research support staff working for the Dr. Kleeman have had technical experience with underwater equipment design.

The next phase of the project involves the deployment and integration of other sensors onto an existing Titan SII submersible remotely operated vehicle for the simultaneous localization and mapping work. Specifically inertial navigation and water speed sensors need to be incorporated. A Kalman filter based localization and mapping approach will be employed. Two basic environments will be used for large scale mapping experiments:

a. Man made structures dominating the features that can be sensed for the purposes of landmark recognition. Examples of this are pipelines, underwater oilrig structures and wharf structures.
b. Natural reef and seabed terrain where landmarks need to be extracted from features of the terrain such as peaks, changes in contours and valleys. This domain is considered to be the more challenging of the two environments and will be attempted last.

3.4 Potential Research Collaboration

A research grant that has been funded partially for the "Underwater Sonar for Simultaneous Localization and Mapping" project by the Australian Research Council for 2000, 2001 2002, for AU$49,000 AU$51,000 AU$53,000 respectively. This funding is less than half of the requested funding levels in the proposal in the first 2 years. Items that need funding are:

Year 2000:

Ph.D. scholarship (AU$24337)

Half of Research Associate Position (AU$24000).

Approximately a third of the budget for underwater sonar transducers, power amplifiers, data acquisition hardware, DSP processors, electronics, printed circuit board manufacturing (AU$11720). This budget item includes the integration of late model DSP devices such as the SHARC DSP devices from Analog Devices. These chips require expensive multilayer (at least 6 layer) printed circuit boards to be fabricated with the anticipated cost of the order of $1000 per new design.

Year 2001

Ph.D. scholarship (AU$24337)

Half of Research Associate Position (AU$25000).

Inertial Sensors and water speed sensors (AU$10000). This item covers the cost of low drift gyro/accelerometer inertial sensor units and low friction water speed measurement devices. These will be mounted on the ROV available for this project.

Year 2002

Ph.D. scholarship (AU$24337)

Fraction of Research Associate Position (AU$11000).

The vast extent of ocean and coastline available to Australia should be a motivating factor for funding research into underwater technology. Sponsorship for co-development, co-research and funding from the international community is both encouraged and welcomed. The ONRIFO **Naval International Cooperative Opportunities in Science and Technology Program (NICOP)** is a potential avenue for new international collaboration initiatives (for information on how to apply see http://www.ehis.navy.mil/nicop.html).

4. Assessment *by CDR Butler and Dr. Jones, ONRIFO*

One area of research of international importance is solving the simultaneous localization and mapping problem for underwater vehicles. ONR's current research and development areas include sensors, communications, navigation, and neutralization technologies which can be integrated into unmanned underwater platforms for the purposes of detection, classification, identification, mapping/reporting and neutralization of moored, bottom and buried mines. The work of Dr. Kleeman is relevant to the interests of ONR particularly in the area of UUV's. Dr. Kleeman has a demonstrated track record in sonar sensing dating back to 1989, in ultrasonic localization, target position estimation and classification, and DSP implementation of sonar hardware for real-time applications. He also has a proven track record in Kalman filtering applications and specifically in target map building and localization. The research environment at the Intelligent Robotics Research Center is ideal for this work since the infra-structure is in place and there is a critical mass of personnel with diverse skills necessary for undertaking a project of this nature. IRRC high-resolution sonar will provide better object detection and classification. In addition, such sonars will allow precise navigation through concurrent mapping and localization (CML), feature mapping and micro-navigation and station keeping. The research being conducted by Dr. Kleeman could provide the sensors crucial to ONR goals, provided Dr. Kleeman is able to transition the sensors from an in-air environment to the undersea environment. ONR has a network of undersea environment experts which has the potential to assist Dr. Kleeman's sensor technology in an undersea setting.

5. Contacts

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